Section D. Science Requirements and Mission Science Performance

D.1 Executive Summary

LISA maps Einstein's relativistic Universe. Gravity dominates the Universe. It compacts matter into planets, stars, galaxies and extremely dense objects such as neutron stars and black holes. Gravitational waves are produced when these most compact objects are themselves combined. These extremely violent events may be the final merger of giant black holes at the centers of merging galaxies, they may be intermediate-sized black holes coming together as the giants grow, they may be the swallowing of a dead star by a massive black hole in the center of a galaxy, or they may be collapsed stars within our own Milky Way, locked in a fatal duet.

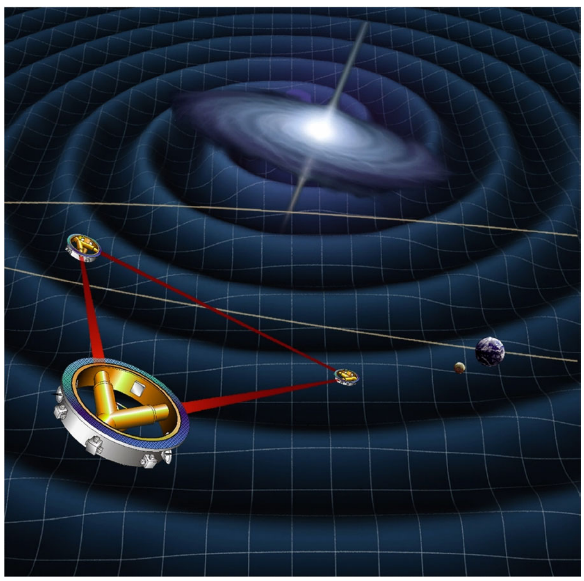

Figure D-1: LISA detects gravitational waves from mergers of compact objects throughout the Universe.

Gravitational waves (ripples in space-time) are produced wherever super-dense objects are closely bound by their mutual gravity. Those waves carry information about their source throughout the Universe, virtually unaffected by intervening matter. The sources experience the most extreme physics in the most extraordinary astrophysical settings known, and gravitational waves carry unique information about them.

The Laser Interferometer Space Antenna (LISA) is a joint European Space Agency (ESA)-NASA project to design, build and operate the first space-based, gravitational-wave observatory. The design concept is based on monitoring distance changes between proof masses in three spacecraft, orbiting the Sun in a triangular formation with 5 million kilometer separations. The constellation of LISA spacecraft (Figure D-1) acts in concert to detect gravitational waves in the frequency band 10^{-4} to 10^{-1} Hz. LISA directly probes the most extreme situations in the Universe, most of which are difficult, or impossible, to observe with conventional electromagnetic observations.

We have a time-critical opportunity to leverage substantial European assets, contingent on prompt action. LISA is an approved Cornerstone Mission in ESA's Cosmic Vision Programme, contingent on NASA participation in the partnership. ESA has agreed to provide three spacecraft, three propulsion modules, gravitational reference sensors, interferometry components, and laser subsystems - $450 M worth of flight hardware. A large team of world-class researchers has been assembled in Europe; ESA member states are establishing institutes to support LISA, in one case staffed by 50 full-time scientists. Backed by extensive prior investments in space-qualified accelerometers, interferometry, lasers and microthrusters, ESA brings significant technologies to the partnership. And, ESA is already funding Small Missions for Advanced Research in Technology (SMART-2), a LISA technology demonstration, including payload, spacecraft, launch and operations.

Our Formulation Phase focuses on technology and mission risk mitigation. Plans, processes and teams for Formulation are in place. Plans, in either draft or finished form, are available for: integrated modeling, Science Requirements, Level 1

Requirements, technology development, integration and test, International Traffic in Arms Regulations (ITAR), partnership with ESA, systems engineering management, and Formulation. Active processes include: system engineering, concept definition, design trade studies, integrated modeling, technology development, requirements capture and management, and risk assessment and mitigation. Active teams include: the International Science Team with working and task groups, system engineering, the Observatory Architecture Team, the Management Team, and the Integrated Modeling Team.

In the LISA design concept, the unique orbits preserve the triangular formation for the life of the mission without station-keeping, and provide the stable environment needed to satisfy the requirements for low disturbances on the proof masses. Disturbances are further controlled through the use of sensitive accelerometers, microthrusters, and other drag-free technologies. Interferometry is used for precisely measuring changes in proof mass separations. Modest lasers, established phase measurement techniques, flight-qualified oscillators, and innovative signal processing enable the required measurement sensitivity to be achieved.

Figure D-2: The 4 km long gravitational wave interferometer at the LIGO Hanford Observatory demonstrates the capability of the gravitational-wave community.

The innovative design draws on technology and experience from precision measurements, ground-based gravitational-wave detectors (Figure D-2) and previous space missions.

The LISA conceptual design is unusually advanced for a mission in Pre-Formulation; it is the product of several Pre-Formulation studies in both Europe and the U.S., and an ESA Phase A industrial study. The design and operations concepts are both straightforward and robust. The demands of the architecture on technology are well understood.

Our technology plan achieves TRL 6 by 2006. The LISA Project is taking a robust approach to technology development with parallel paths and development off-ramps. All technologies were at TRL 3 or higher at the outset; no new inventions are needed. ESA and NASA have started coordinated, parallel development efforts for all technologies. Further, ground-based work fully parallels technology development done for NASA and ESA flight demonstrations, also underway. Hence, LISA is doubly redundant.

LISA also enjoys two types of development off-ramps. First, there are technology alternatives for many subsystems needing development, such as gravitational reference sensors, lasers and microthrusters. Second, the design concept offers flexibility to adapt to technology outcomes. For example, should the requisite laser lifetime prove difficult to obtain, the output power can be reduced for longer life, and the telescope diameter increased to maintain the measurement sensitivity.

The Implementation Team is ready for an FY08 start. NASA and ESA agree on their respective contributions, roles and responsibilities. A Letter of Agreement (LOA) is in place, and a pathfinder document describing a partnering model has been negotiated. NASA supplies the core interferometry components, the payload integration and test, the final integration and test, the launch vehicle and operations. The formulation plan has budget and schedule to prepare for an FY08 start, per NPG 7120.5. The technology plan is scheduled to complete in 2006, retiring technology risks two years before. The System Engineering and Integration (SE&I) contractor will have been working for well over two years prior to an FY08 start, preparing for a rapid acceleration of Implementation activities. NASA risk in Implementation is especially low because ESA provides most of the flight hardware. U.S. costs do not ramp up until ESA hardware has been developed.

D.2 Science Goals and Derived Requirements

LISA is the first space-based gravitational wave observatory. It is exploring not just a new spectral region, but a whole new spectrum, that of gravitational radiation. This section lays out the science goals, the science objectives and the derived science requirements that follow from them. Those requirements will then drive the measurement requirements and measurement technology, laid out in Section D.3, that enable this new science.

D.2.1 Science Goals

The science begins with humankind's understanding of the Universe based on electromagnetic observations, and then explores the Universe through gravity, the force that dominates on the largest scales. This section establishes the foundation for the LISA science goals given in Section D.2.1.2.

D.2.1.1 The Astrophysical Context

One of the most startling revelations to emerge from astrophysics in the last decade is the discovery that black holes are commonplace. "Supermassive" black holes, ranging from 10^5 to 10^{10} times the mass of the Sun (denoted $M_\odot$), are found at the centers of most galaxies. Stellar mass black holes, the final phase of a massive star's life cycle, have been seen in our galaxy and elsewhere. Intermediate mass black holes are thought to play a fundamental role in the build up of supermassive black holes. When these, and other gravitationally compacted objects like neutron stars and white dwarfs, come together in close pairs (see Figure D-3), they make prodigious quantities of gravitational radiation, which leads to further orbital decay, more radiation and eventually merger of the two objects.

The powerful radiation from these binary systems propagates unattenuated across the Universe as a time-varying strain in space-time. This radiation carries direct, detailed information about these extremely energetic, highly relativistic environments. This information probes regimes of gravity and energy that far exceed any other that humans have experienced to date.

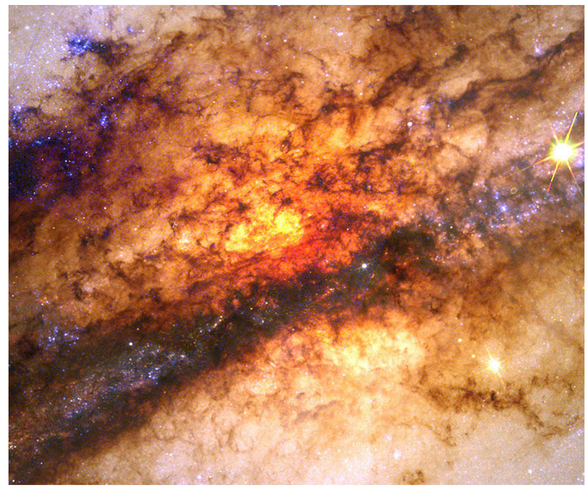

Figure D-3: Centaurus-A has recently merged with a smaller galaxy, stirring up its central bulge.

D.2.1.2 LISA Science Goals

LISA addresses some of the most fundamental topics in astrophysics, cosmology, and relativity. The science of LISA includes such intriguing objectives as: observations of supermassive black hole mergers, the most energetic single events in the Universe; detection of black hole formation out to extremely high redshift ($z > 10$); precision tests of Einstein's Theory of General Relativity; and probes of the first fraction of a second of the Universe (see Figure D-4). LISA is an extremely powerful mission because it provides both guaranteed science through its observations of supermassive black holes and ultra-compact binaries, as well as a huge potential for discovery of exotic and unexpected phenomena.

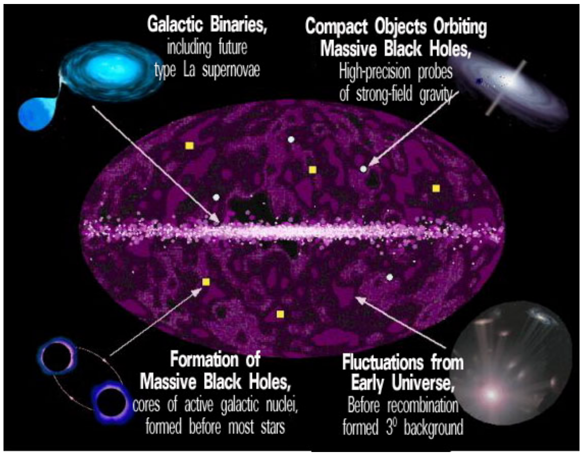

Figure D-4: The gravitational wave sky

LISA's top-level science goals are:

- ***Determining the crucial role of massive black holes (MBH) in galaxy evolution through the detection of MBH mergers.*** We now know that black holes are common in the centers of galaxies, but we do not know how these black holes were formed or what influence they have had on the galaxies in which they reside.
- ***Making precision tests of Einstein's Theory of General Relativity.*** With as many as 10,000 orbits during each inspiral, we can precisely map the knotted structure of space and time around a black hole and determine if the astonishing predictions of Einstein's Theory are correct: the freezing of time and dragging of space around a black hole. These very strong sources enable high precision observations of complex gravitational wave forms predicted by non-linear strong-field General Relativity. These carry detailed information about black hole event horizons, such as how they form and evolve.
- ***Determining the population of ultra-compact binaries in our Galaxy.*** The demographics of the Galactic population of short-period compact binaries and the diffuse galactic background from the compact binary population at longer periods contributes important new knowledge to the study of some of the most extreme endpoints of both stellar and binary evolution.
- ***Searching for gravitational wave emission from the early Universe.*** Detection of any cosmological gravitational wave background would be a discovery of truly fundamental significance and would be the most exciting result from a gravitational wave mission. Millihertz measurements probe energy and length scales that were characteristic of the Universe 10^{-15} seconds (s) after the Big Bang. Because gravitational waves interact very weakly with matter, the Universe was transparent to gravitational waves back to the beginning of the Big Bang.

D.2.2 Science Objectives and Requirements

The science objectives and requirements for the LISA mission have been studied and defined by the LISA International Science Team (LIST). [Ref. D-1] The science goals are achieved through observation of five types of sources:

- Merging supermassive black holes
- Intermediate-mass/seed black holes
- Gravitational captures from nuclear star clusters
- Galactic and verification binaries
- Cosmological backgrounds and bursts.

The following sections lay out the science objectives and science requirements for each source type.

D.2.2.1 Merging Supermassive Black Holes

Observations by the Hubble Space Telescope and others have established that supermassive black holes reside in the bulge-like centers of many, if not most, galaxies. Combined with the fact that most of today's galaxies are built from the mergers of two or more progenitors, this implies that mergers of supermassive black holes are likely to be common occurrences in the Universe (see Figure D-5). Such mergers are largely "dark" in electro-magnetic radiation, but are incredibly strong events when observed via gravitational wave emission. In fact they are the most powerful events in the entire Universe at the time they occur. We do not know how supermassive black holes are formed and how they evolve and thus there are many unanswered questions. The LISA science objectives in observing supermassive black hole mergers include:

- Determine the merger history of galaxies and proto-galaxies out to very high redshift ($z > 10$) and elucidate the role of the central black holes in galaxy evolution. Determine distances and directions to massive black hole mergers, thus enabling searches for possible coincident electromagnetic radiation and corresponding identification of the host galaxy and redshift.
- Determine precision masses and spins for supermassive black holes in galactic nuclei thus constraining formation scenarios.
- Perform precision tests of dynamical non-linear gravity by comparing observations of merger and ringdown (damped oscillations) with numerical calculation of Einstein's equations.

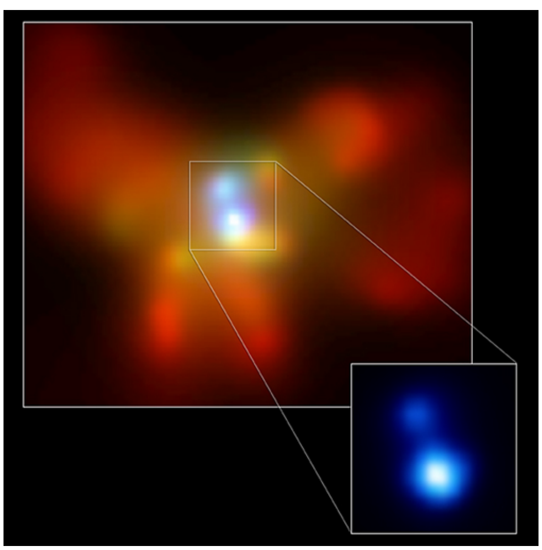

Figure D-5: The supermassive black hole binary recently found in NGC 6240.

LISA Science Requirement (LSR 1):
Sensitivity at low frequencies to detect black hole mergers with constituent masses of 3×10^5 $M_\odot$ (z=1) with an signal-to-noise ratio (SNR) of 2 or larger two months before merger; Sufficient mission duration to provide the possibility of studying many such events.

D.2.2.2 Merging Intermediate-Mass/ Seed Black Holes

Supermassive black holes were probably formed during the so-called "dark ages" (z = 7-30) when luminous galaxies as we know them today were just starting to appear. We know that supermassive black holes were already present very early in the history of the Universe because of their manifestation in active galactic nuclei at high redshift. When during this epoch did supermassive black holes form? Were they built up hierarchically through the merger of many smaller ("seed") mass black holes as predicted by standard cosmology models, or did they grow via gas accretion, or both? Calculation of seed black hole mergers rates in hierarchical models yields rates of 10-1000 per year. The LISA objective is to probe this largely unexplored epoch by searching for high-redshift mergers.

LISA Science Requirement (LSR 2):
Sensitivity to detect merging seed black holes ($\sim 10^3 - 10^5$ $M_\odot$) in proto-galactic fragments at z =7-30.

D.2.2.3 Gravitational Capture from Nuclear Star Clusters

When a compact star is captured from the star cluster in a galactic nucleus and spirals into the supermassive black hole, it can emit detectable gravitational radiation for over 10,000 orbits, thus providing the ability to precisely map the space-time near the black hole event horizon (see Figure D-6). Using this information, we can distinguish between the space-time geometry predicted by Einstein's General Theory of Relativity and others. In particular, we can test the famous "no-hair" theorem of General Relativity that predicts space-time can be characterized by just the mass and spin of the supermassive black hole. In addition to precision probes of the black hole space-time, observations of gravitational capture events with LISA provide new information on the masses and spins of black holes residing in the centers of galaxies, as well as information on the nuclear star clusters, particularly the compact object component of these clusters (e.g. stellar mass black holes and neutron stars).

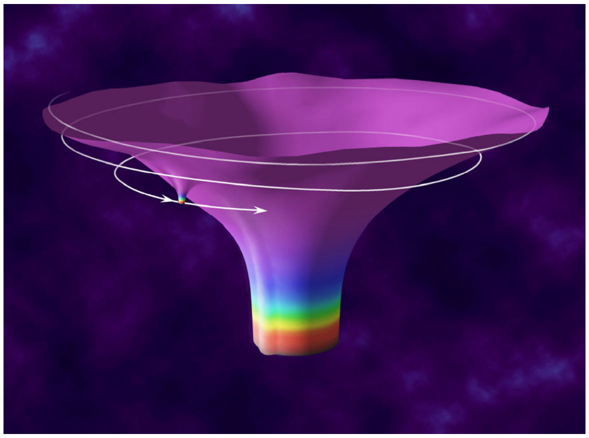

Figure D-6: Space-time of a compact star orbiting a massive black hole.

LISA Science Requirement (LSR 3): Sensitivity to detect at least one gravitational capture event per year at SNR of 10 or larger; mission duration to allow reduction of the background from white dwarf binaries in our galaxy.

D.2.2.4 Galactic and Verification Binaries

An important objective of the LISA mission is to survey the galactic population of close, ultra-compact binaries, i.e., those with periods less than about 10,000 seconds. At periods below about 300 seconds, LISA is able to identify and study approximately 10^4 individual binary systems. Scientific objectives include:

- Production of a complete map of the Galaxy and Halo for compact binary stars with periods shorter than about 300 s, with detailed information on masses, distances, orbital periods, inclinations and orientations. A compact binary star map of the Galaxy and Halo provides significant new information about star formation and stellar evolution.
- Study of white dwarf tides, magnetic fields, structure, and merger scenarios. By studying deviations from the predicted gravitational wave behavior, insight can be gained into tides via loss of angular momentum from the binary, as well as mass quadrupoles due to magnetic fields.

The LISA detection sensitivity is validated, and its response is calibrated by detecting gravitational waves from "verification" binaries, galactic binary systems whose masses and orbits are well known from optical, infrared, or x-ray measurements. Currently there are more than 15 identified galactic binary systems that can be used as verification binaries. Though this is not a science objective leading to new knowledge, it does provide strong confirmation of a new instrument studying a new spectrum.

LISA Science Requirement (LSR 4): Sensitivity to provide SNR of 20 for 50% of the resolvable binaries; mission duration to separately determine sky position and period derivatives; measure diffuse Galactic background down to periods of 10^4 seconds; sensitivity, mission duration, and polarization measurement capability to detect at least three verification sources with an SNR of at least 10 and determine their directions, period derivatives, and orientations.

D.2.2.5 Cosmological Backgrounds and Bursts

While the gravitational radiation due to standard models of cosmology (so-called slow-roll inflation) is not detectable, other sources of a stochastic gravitational wave background may very well be detectable. Possible sources include: an electroweak phase transition, a brane-world dimensionality transition, cosmic string kinks and cusps, and alternate types of inflation (other than slow roll). LISA has the ability to detect the amplitude of the stochastic isotropic gravitational wave background at frequencies between 10^{-4} and 10^{-1} Hz, to a level corresponding to 10^{-5} of the microwave background energy density.

Possible cosmological sources of bursts include cosmic string kinks and cusps, collapse of the earliest Very Massive Objects, and formation of intermediate mass black holes.

LISA Science Requirement (LSR 5): Capability to separate instrumental background from cosmic diffuse background; a non-Gaussian instrumental glitch rate less than a few per day.

D.2.2.6 Minimum Science Mission Requirements

The LISA Science Requirements 1-5 given in the previous five sections are used for the flow down to mission performance requirements and instrument requirements. To motivate the requested "minimum measurement parameters for mission success" given in Section D.3.1, we provide the associated science requirements here. The minimum science requirements consist of a subset of the full LISA Science Requirements. Specifically, LISA must meet **only** the following minimum science requirements:

- A modified LSR 1 (Merging supermassive black holes: meet the stated sensitivity requirement above 1 mHz; relaxed sensitivity at 0.1 mHz; two separate one-year integration times – see Section D.2.3.1).
- A modified LSR 4 (SNR > 10 for 20% of resolvable compact binaries; detection of one or more verification binaries at SNR > 10).

This set of reduced requirements describes a very robust science mission. They retain full capability for detection of supermassive black holes in the critical mass range from $3x10^5$-10^7 $M_\odot$, albeit with a reduction in the time period before merger over which gravitational waves could be detected. It provides a wealth of information on thousands of individual compact binaries in the galaxy. It also provides definitive demonstration of LISA detection of gravitational waves and firm instrument calibration. The minimum requirements are well matched to the level of technical performance to be demonstrated by the SMART-2 mission in 2006.

Contrasting the full set of science requirements to these minimum requirements, we see that the full set principally adds the capability to explore lower black hole mass ranges (i.e. the so-called seed black holes), and the capability to detect gravitational capture events. These extremely exciting possibilities are the rationale for the nominal measurement requirements.

Observations of lower mass black holes allow us to address the question of how the massive black holes that we find in the centers of galaxies actually came into being. These observations allow us to probe extremely high redshifts ($z > 10$) and detect compact stars being captured by massive black holes, the most stringent test of Einstein's Theory.

D.2.3 Connecting Science Objectives to Mission Requirements

A generic model of gravitational wave detection is useful for connecting science objectives and requirements to mission performance requirements, and ultimately to subsystem requirements. While this isn't necessary for conventional space science instrumentation (e.g., telescopes, camera, spectrometers), it is for gravitational wave detectors. The next section provides a generic model and the following section then ties the science objectives to the mission requirements.

D.2.3.1 Detecting Gravitational Waves

Gravitational waves are a periodic strain in space-time – a time-varying, fractional change in any distance. Even for the powerful sources that LISA detects, the fractional change can be as small as $10^{-20}/\sqrt{\text{Hz}}$. [Note that *amplitude* spectral densities are commonly used in gravitational wave detection because the detectors measure amplitude rather than power, as do traditional electromagnetic detectors.] The size of this strain is a testimony to the fundamental weakness of the coupling of gravitational waves to matter.

Gravitational waves are detected by measuring changes in separations between an array of proof masses. When these proof masses are shielded from extraneous disturbances, they serve as measurement reference points tied to space-time.

Since very sensitive measurement systems typically measure displacement rather than strain, the detection of gravitational waves is made easier if the separation of the proof masses is as large as practical so that the displacement associated with the fractional change is large. This argues for a detector arm length of millions of kilometers.

Further, this detector scale should be appropriate to the wavelength of the gravitational radiation expected. The most easily detected sources (see Table D-1) lie in the frequency band from 10^{-4} to 10^{-2} Hz. Ideally, the arm lengths should be smaller than the wavelength of the gravitational waves. Consequently, the science also argues for arm lengths of millions of kilometers.

These considerations establish the four defining requirements on a gravitational wave detector.

- The principal requirement associated with the proof masses is that they not experience any disturbance that causes an acceleration comparable to that caused by gravitational waves.
- The principal requirement on the measurement system is that it be sensitive enough to detect the small changes in the separation of the proof masses caused by those sources.
- The arm length must match the target measurement bandwidth, and be long enough to support the requisite sensitivity.
- Finally, the integration time (reconstructable coherent data collection - i.e., allowable gaps) must be compatible with the source so as to support the requisite sensitivity.

We use these four requirements as measurement performance parameters to characterize a generic gravitational wave detector in the following sections. They set the sensitivity to the strain representing the strength of the gravitational wave signal. Note that though displacement data are taken, strain is the fundamental science measurement returned by the mission.

Unlike electromagnetism, gravity has no negative charge. Consequently, the lowest symmetry of the waves is quadrupolar rather than dipolar. However, there are still two polarizations to detect. With available measurement technology, this requires monitoring three arm lengths with restrictions on the angles between them.

D.2.3.2 Science Objectives-to-Measurements-to-Mission-Traceability

With science goals objectives and requirements established, and with a model for gravitational wave detection, we now lay out the logic connecting the diverse science goals to the critical subsystem requirements that control the design and drive technology development. The remainder of Section D is largely focused on connecting the science requirements to an instrument design concept, and finally to defining subsystem requirements. In practice, this process is highly iterative, but here we define it as a linear progression. Figure D-14 (Foldout D-1) illustrates this flow.

Science goals (Section D.2.1) lead to science objectives and requirements (Section D.2.2), organized by the five types of astrophysical sources of gravitational waves. Observation of each of these source types imposes a different set of requirements, e.g., strain sensitivity, frequency range and integration time. These sets are summarized in Section D.3.1. The "minimum science requirements for mission success" are defined in Section D.2.2.6 by relaxing nominal requirements and relinquishing others.

Next, using the generic prescription for detecting gravitational waves from the previous section (Section D.2.3.1), we choose a single set of measurement requirements (i.e., disturbance level, measurement sensitivity, arm length, integration time) that encompasses the science requirements for all source types. The performance expected from the chosen set of measurement requirements is captured mainly in the sensitivity curve presented in Section D.3.1. The instrument concept must

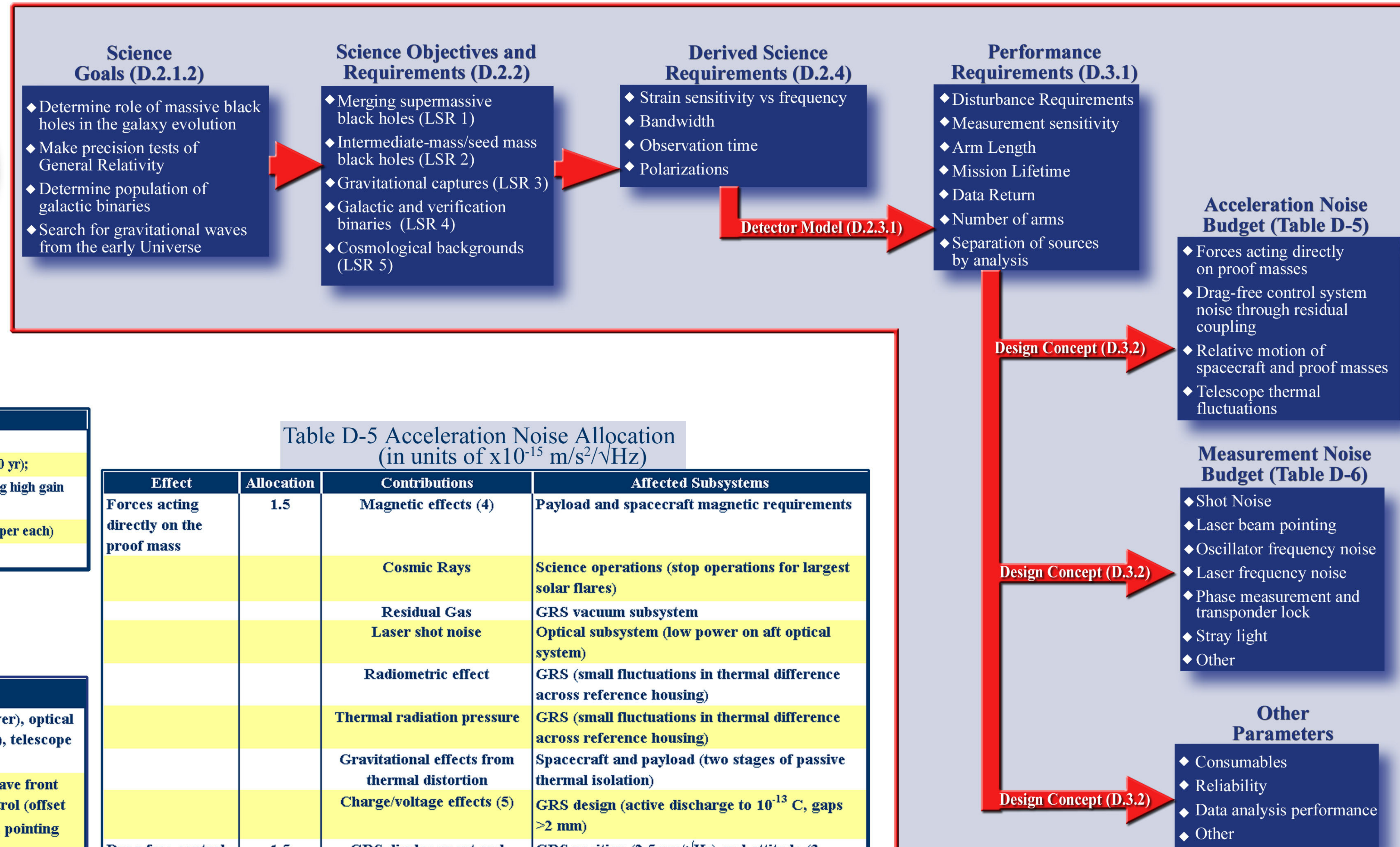

Figure D-14
Connecting science goals to subsystem requirements.
See §D.2.3.2 for further discussion.

Table D-4 Impacts of System Level Measurement Requirements

Effect	Requirement	Affected Subsystems
Arm length	$5x10^{6}$km	
Mission lifetime	5 yr nominal	All subsystems (lifetime); thrusters (fuel for 10 yr);
Data return	90% over 1 yr	All subsystems (reliability); comm. (re-pointing high gain antenna <1/week)
Number of arms	3	Spacecraft (3); payload (2 optical assemblies per each)
Source separation	See Science Requirements	Waveform accuracy; science data analysis

Table D-6 Displacement Noise Allocation (in units of 10^{-12} m/s²/√Hz)

Effect	Allocation	Number	Affected Subsystems
Shot noise (photon statistics)	11	4	Laser subsystem (1 W power), optical subsystem (50% efficiency), telescope (30 cm aperture)
Laser beam pointing noise	10	4	Optical subsystem (λ/40 wave front error); active pointing control (offset pointing error <$3x10^{-8}$ rad, pointing stability $8x10^{-9}$ rad/√Hz)
Oscillator frequency noise	10	1	Phase measurement (USO Allen variance of $2x10^{-13}$ at 10^{4} s), TDI clock frequency noise correction
Residual laser frequency noise	10	1	Laser subsystem (frequency stabilization to 30 Hz/√Hz), TDI frequency noise correction (knowledge of arm length to 10 km and arm length difference to 200 m)
Phase measurement and transponder lock	5	4	Phase measurement subsystem ($5x10^{-6}$ cy/√Hz), laser subsystem (offset phase lock)
Stray light effects	5	4	Laser subsystem (offset locking, frequency stabilization)
Other substantial effects	3	32	Interferometry Measurement System (careful mechanical and optical design)

Table D-5 Acceleration Noise Allocation (in units of $x10^{-15}$ m/s²/√Hz)

Effect	Allocation	Contributions	Affected Subsystems
Forces acting directly on the proof mass	1.5	Magnetic effects (4)	Payload and spacecraft magnetic requirements
		Cosmic Rays	Science operations (stop operations for largest solar flares)
		Residual Gas	GRS vacuum subsystem
		Laser shot noise	Optical subsystem (low power on aft optical system)
		Radiometric effect	GRS (small fluctuations in thermal difference across reference housing)
		Thermal radiation pressure	GRS (small fluctuations in thermal difference across reference housing)
		Gravitational effects from thermal distortion	Spacecraft and payload (two stages of passive thermal isolation)
		Charge/voltage effects (5)	GRS design (active discharge to 10^{-13} C, gaps >2 mm)
Drag-free control system noise through residual coupling	1.5	GRS displacement and angular readout noise	GRS position (2.5 nm/√Hz) and attitude (3 nrad/√Hz) sensing
		Residual coupling	Payload gravity gradients, charge control subsystem, electrostatic sensing and forcing
Relative motion of spacecraft and proof mass	1.5	Thruster noise	Low noise microthrusters (<0.1 μN/√Hz)
		Solar radiation pressure noise	Spacecraft area normal to solar radiation
		Residual coupling	Payload gravity gradients, charge control subsystem, electrostatic sensing and forcing,
		Drag-free control gain	DRS control laws (high gain at 10^{-4} Hz)
Telescope thermal fluctuations*	1.5	Thermal fluctuations	Spacecraft and payload (passive thermal isolation)
		Thermal expansion	Telescope (construction of low CTE materials)

**Note that the "acceleration" noise contributors are those that give displacements with a $1/f^2$ frequency dependence, whereas the "displacement" noise contributors are frequency independent,at least in the measurement bandwidth.*

There is one Interferometry Measurement System noise effect that has the frequency behavior of an acceleration, thermal expansion of the primary-secondary spacer in the telescope owing to thermal fluctuations. This has been carried along with the acceleration noise budget for simplicity of the presentation.

achieve the performance represented by this model sensitivity curve.

The minimum measurement parameters required for mission success are also shown in the sensitivity curve in Section D.3.1. These derive from the "minimum science requirements for mission success" given in Section D.2.2.6. **This performance is supported by our ground-based technology development effort and it is used as a performance margin throughout this report**.

Subsystem requirements are derived from our well-developed concept for a gravitational wave detector. The LISA reference design is described in Section D.3.2 – 3.4. Additional Implementation details can be found in Sections E and F. Finally, error allocations on instrument systems are summarized in Section D.7 and Tables D-4, D-5, and D-6 linking to subsystem requirements found on Foldout D-1.

D.2.4 Derived Science Requirements

The LISA International Science Team has produced a quantitative set of performance requirements from the science requirements given in Section D.2.2. [Ref. D-1] These are given in Table D-1 as required gravitational wave strain sensitivity at a set of frequencies and an observation time for each source type. The bottom row of the table indicates the most stringent requirement at each frequency to be accommodated by the generic detector model.

The sensitivity requirements in the table describe a gravitational wave receiver that operates over a frequency band somewhat wider than 10^{-4} to 10^{-2} Hz, with best sensitivity in the top half decade of frequency. We take this to define a target measurement bandwidth (MBW) of 10^{-4} to 10^{-1} Hz. This is the bandwidth over which the derived requirements are met. We can expect that any plausible detector has, at worst, a sensitivity that deteriorates slowly outside this band.

The science performance requirements here have been stated for a single polarization. However, LSR 5 calls for the capability to separate instrumental noise from a background. As mentioned in Section D.2.3.1, gravitational waves have two polarizations. By enforcing the mission science performance requirement for both polarizations, we can meet LSR 5. This amounts to a requirement for measuring three arm lengths, rather than two arm lengths, to realize two strain measurements. This performance requirement does not have a substantial implementation burden, but it does have a number of benefits in science return, replication costs and mission robustness. It is not required for the minimum requirements for science success.

Table D-1: Quantitative science requirements, in units of gravitational wave strain spectral amplitude, $(S_h[f])^{1/2}$ in units of $1/\sqrt{Hz}$.

Source	Spectral Amplitude ($1x10^{-4}$Hz)	Spectral Amplitude ($1x10^{-3}$ Hz)	Spectral Amplitude ($5x10^{-3}$ Hz)	Spectral Amplitude ($1x10^{-2}$ Hz)	Observation Time (Yrs)
Merging supermassive black holes	$4x10^{-17}$	$8x10^{-19}$	$1x10^{-19}$	N/A	5 (3 arms required)
Intermediate-mass/seed black holes	N/A	$3x10^{-19}$	$2x10^{-20}$	$2x10^{-20}$	1
Gravitational capture from nuclear star clusters	N/A	$3x10^{-19}$	$1x10^{-20}$	$1.5x10^{-20}$	3
Galactic binaries and verification binaries	N/A	$3x10^{-19}$	$3.5x10^{-20}$	N/A	2
Cosmological backgrounds	N/A	N/A	N/A	N/A	1 (3 arms required)
Overall Requirement	**$4x10^{-17}$**	**$3x10^{-19}$**	**$1x10^{-20}$**	**$1.5x10^{-20}$**	**5** (3 arms required)

D.3 Mission Science Performance

D.3.1 Performance Requirements

As described in Section D.2.3.1, there are four main parameters of a space-based gravitational wave detector that combine to establish the sensitivity and useful bandwidth: spurious accelerations of the proof masses from unwanted disturbances, sensitivity in the measurement of changes in proof mass separations, arm length (i.e., proof mass separation being monitored), and integration time. These four parameters combine in different ways to define instrument sensitivity.

Arm length is roughly set by the frequencies of the target sources. Low frequency strain sensitivity of the detector is controlled by the ratio of spurious acceleration noise to arm length, and middle and high frequency strain sensitivity is set by the ratio of measurement sensitivity to arm length, convolved with instrument response. LISA target sources have slowly varying frequencies so that sensitivity is generally improved by longer integration times. Values of these parameters, optimized to meet the science requirements in Table D-1, are given in Table D-2.

Table D-2: Principal Mission Performance Requirements

Parameter	Requirement
Arm length	5×10^{6} km
Spurious acceleration (per proof mass)	3×10^{-15} m/s^2/√Hz, 0.1 to 1 mHz
Measurement sensitivity (round trip)	4×10^{-11} m/√Hz, 1-100 mHz
Integration time	1 year

These nominal values yield the sensitivity curve in Figure D-7. This figure also displays the sensitivities taken from Table D-1. The sensitivity curve based on the assumed values for the disturbance level and measurement sensitivity satisfies all of the science requirements. Hence, this sensitivity curve represents the principal measurement requirements on the LISA conceptual design.

Similarly, the "minimum science requirements" from Section D.2.2.6 are used to determine the "minimal measurement parameters for mission success" given in Table D-3. The associated sensitivity curve is also shown in Figure D-7 for comparison with the nominal mission performance and the science requirements.

Table D-3: Minimum Measurement Parameters for Mission Success

Parameter	Requirement
Arm length	5×10^{6} km
Spurious acceleration (per proof mass)	3×10^{-14} m/s^2/√Hz, 0.1 to 1 mHz
Measurement sensitivity (round trip)	4×10^{-10} m/√Hz, 1-100 mHz
Integration time	1 year

D.3.2 Instrumentation

The "instrument" that detects gravitational waves is the three cooperating spacecraft and not the "payload" on each LISA spacecraft. Hence the three spacecraft operating in concert comprise the science instrument. The payload and spacecraft are integrated to meet the disturbance requirements.

The LISA instrument can be easily understood by describing first the measurement concept and then the two main subsystems of the science instrumentation, the Disturbance Reduction System (DRS) and the Interferometry Measurement System (IMS). Further details of the implementation can be found in Sections E and F. The measurement concept is described in much greater detail in [Refs. D-2, D-3].

D.3.2.1 The LISA Measurement Concept

The LISA gravitational wave detector measures time-varying strains along three arm lengths. The arm lengths are 5 million kilometers long and arranged in an equilateral triangle. This basic instrument scale is compatible with the aggregate signal band of the gravitational wave sources listed in Table D-1. The sensitivity of the instrument described here satisfies the mission performance requirements in Table D-2.

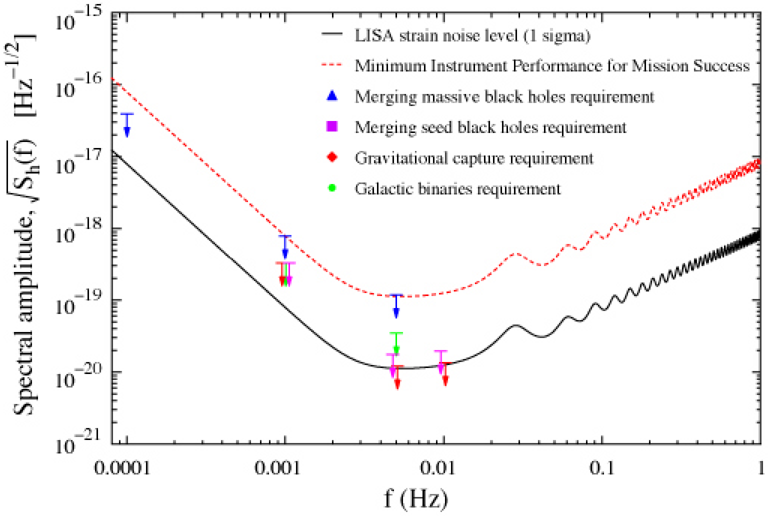

Figure D-7: Required measurement performance, minimum instrument performance or mission success and science requirements.

An array of six proof masses is deployed so that one proof mass defines each end of each arm length. That is, there are two proof masses in a single spacecraft at each vertex, separated by ~1 m. Laser beams are transmitted in both directions along the arms to interferometrically monitor changes in their length. Interferometry is the only known metrology technology that can operate over the desired distances with the required sensitivity.

A spacecraft at each vertex houses the two proof masses and the interferometry equipment associated with the endpoints of the two arm lengths (see Figure D-8). The formation of three spacecraft is obtained by placing them in solar orbits chosen to maintain a stable equilateral triangle. The center of the triangle follows the Earth in its orbit about the Sun by nominally 20°. Thus the array of proof masses defines three long arms whose lengths are monitored for changes caused by the passage of gravitational waves.

Changes in arm lengths are measured by the phase of the laser beam sent from one spacecraft to the second spacecraft at the far end of that arm. At the second, distant spacecraft, the beam is reflected off the proof mass and interfered with a small amount of power from a local laser whose frequency is offset-locked to the incoming beam. Most of the power from the second laser is transmitted back to the first spacecraft where it is again reflected off the proof mass and interfered with a small amount of power from the local laser. This transponder scheme avoids the double diffraction loss of a passive reflective system and returns the original phase information to the first spacecraft, modified by roundtrip propagation over the arm.

The science signal appears as variations in the time of phase front arrivals, that is, a phase modulation of the beat signal. Were the laser frequency perfectly constant, the beat signal from the final interference would yield the science signal. Even the frequency-stabilized laser has residual frequency noise, as does the clock used in the phase measurement. Hence, beat signals from different arms must be combined to correct for laser and clock frequency noise. This process, called Time Delay Interferometry and described in Section D.3.2.3 below, is a generalization of the frequency noise cancellation accomplished by a Michelson interferometer operating at the white light fringe.

This design concept has several important features. The orbital motion of the formation causes amplitude, frequency and phase modulation of the detected signal that encodes the direction to a gravitational wave source. The three arm length measurements detect two polarizations of incident gravitational waves simultaneously. The

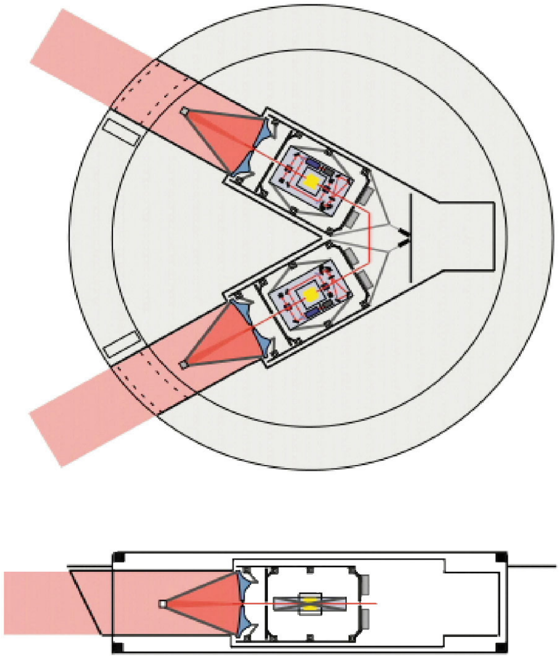

Figure D-8: LISA payload within the spacecraft.

three spacecraft are identical, and their payloads have two identical optical assemblies and proof masses associated with the ends of the two arms at that vertex. This redundancy ensures graceful degradation in the event of failure; up to two optical assemblies can fail causing the loss of only one polarization, so long as they are not in the same spacecraft.

D.3.2.2 Disturbance Reduction System

In order for the array of proof masses to serve as measurement reference points in a gravitational wave detector, they must not be disturbed by unwanted forces at a level that would mask the effects of gravitational waves in the signal band of the detector. Many aspects of the LISA design concept are motivated by the need to reduce disturbances on the proof masses. The acceleration specification is given in Table D-2. In this section, we describe those disturbances and strategies for reducing them. These topics are discussed in much greater detail in [Ref. D-2, D-3, D-4, D-6, D-8]. Detail design choices are described in Section E. Important requirements on DRS subsystems or components are reported in Section D.3.3.2. The block diagram, including the primary instrument interface between the DRS and the IMS, is shown schematically in Figure D-10.

In this section, we describe those disturbances and strategies for reducing them. These topics are discussed in much greater detail in [Ref. D-2, D-3, D-4, D-6, D-8]. Detail design choices are described in Section E.

Significant instrument requirements on the DRS subsystems or components are reported in Section D.3.3.2.

Functions of the DRS

The central component of each DRS is the proof mass that is completely enclosed by a housing rigidly attached to the spacecraft. Along the measurement direction, the proof mass is allowed to fall freely, the housing senses its relative position and orientation with capacitive sensors, and the spacecraft thrusters are commanded to continuously center the proof mass. Along other degrees of freedom, electrostatic forces are applied to center the proof mass. This is called "drag-free" operation, and was pioneered by the TRIAD mission over 30 years ago. The spacecraft follows the orbit of the sheltered proof mass along the measurement degree of freedom. Drag-free operation reduces disturbances caused by spacecraft motion carrying spatial force gradients across the proof mass.

The subsystem which includes the proof mass and its housing is called the Gravitational Reference Sensor (GRS). It provides sensing for spacecraft station-keeping control as well as sensing and forcing for proof mass station-keeping. The GRS also provides charge control, proof mass caging, thermal isolation and other functions. The drag-free control system also requires small thrusters capable of ~50 μN thrust, linear control, and low noise (<0.1 μN). Drag-free control technology is a major technology development area.

Disturbance Reduction

There are two ways that disturbances affect proof masses. First, there are disturbances that act directly on the proof mass. Examples include the interplanetary magnetic field, cosmic rays, residual gas molecules, differential radiation pressure, and voltage/charge fluctuations on the proof mass and surroundings. Second, any residual motion of the spacecraft relative to the proof mass will cause spatial gradients of forces arising in the spacecraft to apply time-varying forces on the proof mass. Examples of these forces are gradients in the spacecraft self-gravity and the electrostatic interaction between spacecraft and proof mass. The residual motion of the spacecraft relative to the proof mass is caused by any disturbance force acting on the spacecraft, such as thruster noise or variations in the solar photon pressure.

The LISA orbits are an important first step in controlling disturbances. The environment at 1 AU is very benign. The largest ambient disturbance is in the solar radiation pressure noise. Solar wind and micrometeorite effects are negligible. Thermal variations in the measurement band are set by variations in the solar irradiance (~0.13% at 1 mHz). Longer-term thermal variation is led by the effect of the orbital eccentricity on solar input, well away from the measurement band. There is neither the atmospheric drag nor the radiation environment associated with low Earth orbits.

Drag-free operation gives a high degree of isolation between spacecraft disturbances and the proof mass. The spacecraft and proof masses are separated everywhere by a 4 mm gap, and force gradients arising in the spacecraft only affect the proof mass through the residual relative motion in the MBW. Furthermore, the design of the GRS is chosen to reduce disturbances arising from thermal, electrostatic and residual gas effects.

Many design features of the LISA concept address specific disturbances. Some important examples are:

- The thermal design of the spacecraft and payload is engineered to achieve tight tolerances on the thermal gradient and thermal gradient variation across the proof mass housing.
- The proof mass is made of an alloy with extremely low magnetic susceptibility.
- The charging of the proof mass by cosmic rays is electrostatically monitored, and actively cancelled with UV light.
- The gaps between the proof mass and its housing are made large to reduce coupling of patch fields (residual patches of electrostatic charge) on the gold-coated surfaces.

Many other steps are taken to reduce disturbances to acceptable levels.

D.3.2.3 The Interferometry Measurement System

The Interferometry Measurement System (IMS) monitors changes in the arm lengths to the requisite precision by a system of laser beams and phase measurements. This section gives an overview of the architecture and major subsystems. Extended descriptions can be found in [Ref. D-2, D-3, D-7].

The LISA measurement system employs a laser transponder system to monitor the relative changes in the distances between proof masses at different corners of the triangular array. The incoming beam at each end of each arm is interfered with the outgoing beam, and the phase of the resulting beat signal is measured as a function of time. The outgoing beam at each end of each arm is interfered with the outgoing beam at the adjacent end, and again the phase is measured, making a total of 12 phase time series. The interferometer architecture is shown schematically in Figure D-9.

By suitably combining these phase signals, delayed by an appropriate propagation time, the laser frequency noise, which is orders of magnitude larger than the gravitational wave signal, cancels in some signal combinations, and the gravitational wave signal does not. In other signal combinations, the gravitational wave signal nearly cancels, but instrumental noise does not, effectively producing a simultaneous instrument noise monitor. This signal combination technique, called Time Delay Interferometry (TDI), was specifically developed for LISA, and is analogous to the white light fringe condition of Michelson interferometers, generalized to unequal arms.

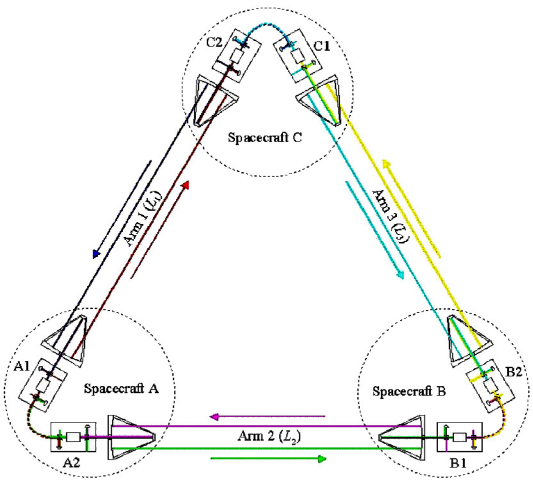

Figure D-9: Transponder system and phase comparison between two lasers on same spacecraft.

Several features of the IMS affect technology development and subsequent implementation: frequency and intensity stabilized lasers; information for pointing the optical assemblies and spacecraft acquired by the optical system; laser beams carrying data between the spacecraft for TDI, a ranging tone for arm length measurement, and a clock tone for clock frequency noise correction.

Important requirements on IMS subsystems or components are reported in Section D.3.3.2.

Optical Layout

The optical layout of LISA can be understood by examining one of the six identical optical assemblies (Figure D-10). There are two optical assemblies in each spacecraft. An optical assembly consists of an 'optics block,' a transmit/receive telescope, and a structural cylinder. The optics block is made of an ultra-low thermal-expansion material and carries the interferometry optics, the photodetectors, the laser stabilization cavity, and the GRS with the proof mass. A fiber-coupled solid-state laser subsystem feeds the optical system. Another optical fiber system carries light in both directions between the two optical assemblies on the spacecraft.

Figure D-10 illustrates the interrelationship of IMS subsystems, and the mechanical, electrical, and optical interfaces with the GRS. Important requirements on IMS subsystems or components are reported in Section D.3.3.2.

The optical system performs several functions. Most of the laser power is reflected off the main beamsplitter and sent out through the beam-expanding telescope. A small amount of the local light is sent to the triangular stabilization cavity to frequency stabilize the laser. Another small amount is bounced off of the backside of the proof mass and coupled into the fiber going to the other optical assembly for phase comparison with that laser. Still another small amount of power is beat with light coming out of the same fiber from the other assembly for a phase comparison. Beam separation is achieved through polarizing beamsplitters and manipulation of polarization.

Incoming light is compressed by the telescope, passed through the main beamsplitter, reflected off of the proof mass, and combined with a small amount of local laser power on the main beamsplitter to form the primary fringe on the main quadrant photodiode. The four elements of the photodetector are used to derive pointing information. A small amount of incoming light is also diverted to a small CCD (not shown in Figure D-10) for pointing information.

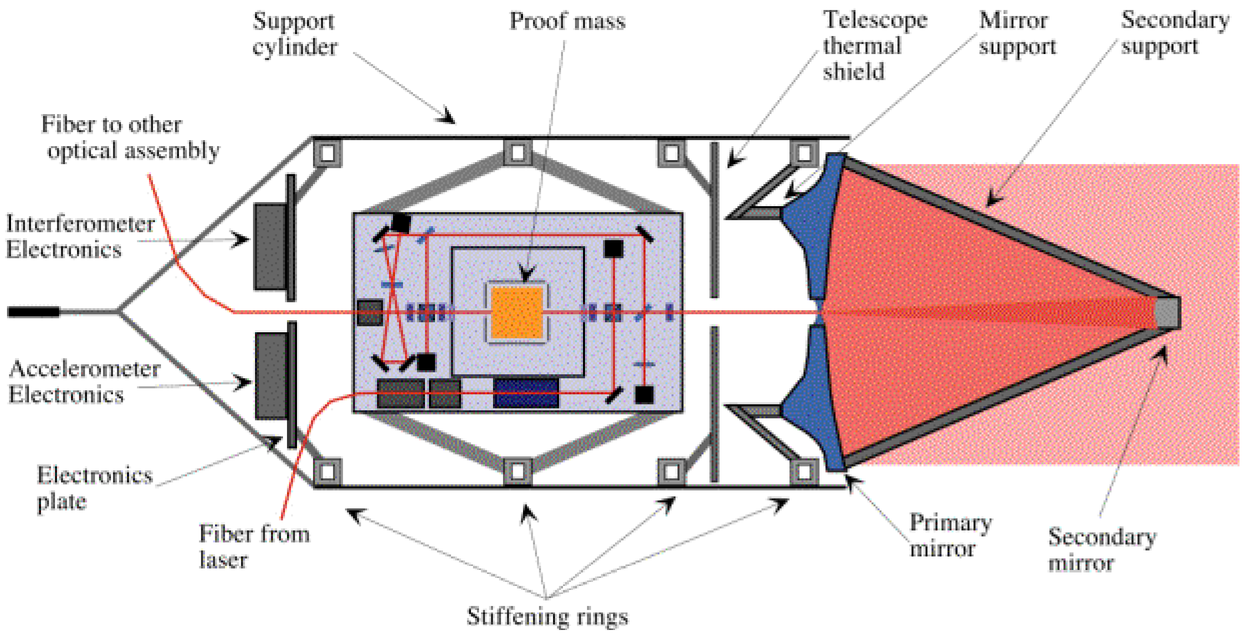

Figure D-10: Schematic of a LISA Optical Assembly. Color key: optical block (pale blue) with attached gravitational sensor and its proof mass (yellow square), telescope (blue primary mirror, grey secondary).

Laser Subsystem

The laser subsystem is built around fiber-coupled, monolithic solid-state lasers. These conventional infrared lasers, operating at a wavelength of 1.064 µm, are naturally compact, reliable, power-efficient, and readily stabilized. A laser subsystem (Figure D-11) includes a laser, an optical isolator, an electro-optic modulator, and a fiber coupler. There is one laser subsystem and one spare for each optical assembly, mounted on a heat sink with active thermal control.

The LISA design calls for 1 W laser, frequency and amplitude stabilized, with a five-year lifetime requirement and a ten-year goal.

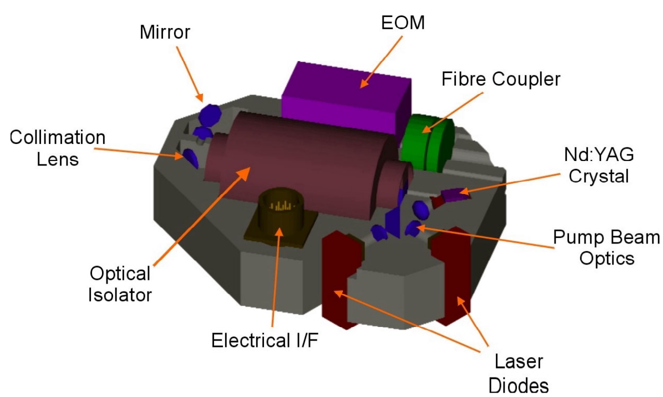

Figure D-11: LISA laser subsystem. Color key: fused silica spacer (gray) laser diodes, Nd:YAG crystal (dark purple).

Telescope

The transmit-receive telescope functions as a 60:1 beam-expander/compressor for coupling the laser beam between the long path and the optics block. This application demands high optical path stability because the primary-secondary distance is traversed twice in the measured arm length. The interaction of pointing variations and wave front errors at the distant spacecraft demands moderately low wave front error.

The reference design calls for a 30 cm F/1.4, afocal Dall-Kirkham design, constructed of an ultra-stable material such as Zerodur™, Ultra-Low Expansion (ULE™) or fused silica. The alignment and mirror figure tolerances have been readily achieved in similar small telescopes for space flight. The optical path length stability is being demonstrated in the technology development effort.

Phase Measurement

The principal measurement is performed in each optical assembly on the interference of the incoming beam from the distant spacecraft and the local laser. The resulting beat signal has several important constituents: the spacecraft-spacecraft Doppler frequency; the differential laser frequency noise; the gravitational wave signal; a ranging tone; a clock reference tone; an offset frequency imposed on the distant laser; and data modulated onto the beam by the remote spacecraft.

The measured quantity is the number of cycles in time intervals clocked by an ultra-stable oscillator. In order to correct for the laser frequency noise, the dynamic range of the phase measurement system must exceed 10^9, which is achieved by a counting system. The phase measurement sensitivity must be less than 5×10^{-6} cycles/$\sqrt{\text{Hz}}$ from 10^{-3} to 1 Hz.

The Doppler frequency derives from natural orbital effects that cause semi-annual changes in the spacecraft separation. This frequency varies on annual time scales between dc and 15 MHz depending on the particular arm and the time of year. The combination of Doppler frequency and transponder offset frequency constitutes a baseband frequency on which the gravitational wave signal appears as a phase modulation, and which can be used for heterodyne detection.

The ranging tone, clock reference tone, and data modulation are kept many decades of frequency away from the science signal so as not to contaminate the phase measurement. The ranging tone provides information about the arm lengths for use in the laser and clock frequency noise correction. The clock tone is used for clock frequency control and correction. Data modulation is used to pass phase measurement information between the three spacecraft for TDI signal processing.

The interference of a local laser with the beam from the other optical assembly in the same spacecraft produces a beat signal without a Doppler component, a gravitational wave signal, a ranging tone, a clock tone, or a data modulation. This phase measurement is simpler and proceeds as above.

Laser and Clock Frequency Noise Correction

Laser frequency noise plays a significant role in the phase measurement because the slightly unequal arm lengths bring it back into any comparison of two arms. Similarly, frequency noise on the oscillators generating the timing intervals comes back into the measurement as an error in the accumulated phase measurement. TDI corrects both of these errors.

The LISA interferometer is unusual in that the optical signal from one arm is not interfered with that from another. The returning beam is interfered with the local laser, and the local laser is similarly compared with the other laser in the same spacecraft. The two phase signals from each of the six optical assemblies constitute a chain of signals referenced pair-wise with each other, but with varying transit-time delays between them.

The signals are combined to extract relative arm length changes through TDI. In effect, TDI uses information about the arm lengths to combine the phase signals with the appropriate transit-time delays so as to cancel the common-mode laser and clock frequency noise. TDI and its performance are described in much greater detail in [Ref. D–7].

Pointing

The IMS requires that the optical assemblies be pointed toward their respective distant spacecraft and that the proof masses be oriented to reflect the incoming beam onto the main photodetector. Pointing control of the assemblies is determined by the control laws of the DRS and carried out by the thrusters and the articulation mechanism between the two optical assemblies. The IMS provides sensing for those control loops through its quadrant photodiode and a small CCD. The quantitative pointing requirements are discussed in Section E.4.5.

D.3.3 Mission Approach

The LISA gravitational wave detector places constraints on the selection of orbits and the performance of the spacecraft subsystems. By contrast, the operations are extraordinarily simple.

D.3.3.1 Mission Design

The geometry of the proof mass array is established by the operational orbits, into which the three spacecraft are inserted. **Those heliocentric orbits minimize changes in the differences of the arm lengths over the operational life of the mission, without orbital maintenance.** The three heliocentric orbits that satisfy that condition result in the three spacecraft orbiting in a triangular formation whose plane is inclined 60° with respect to the ecliptic. The formation follows 20° behind the Earth for ease of communication (see Figure D-12 and D-13).

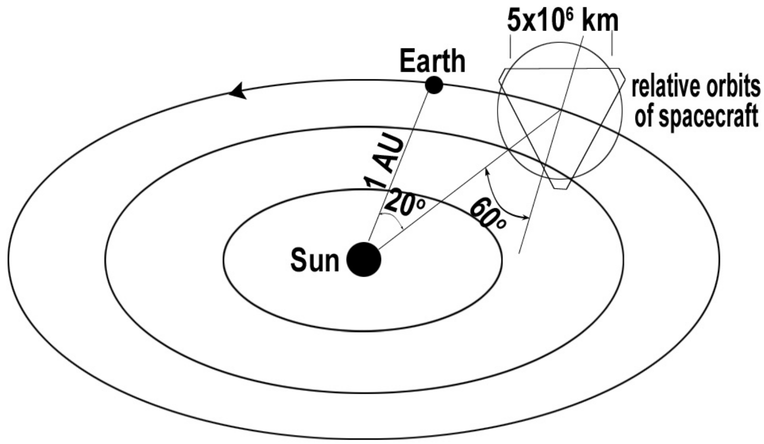

Figure D-12: LISA Formation, not to scale

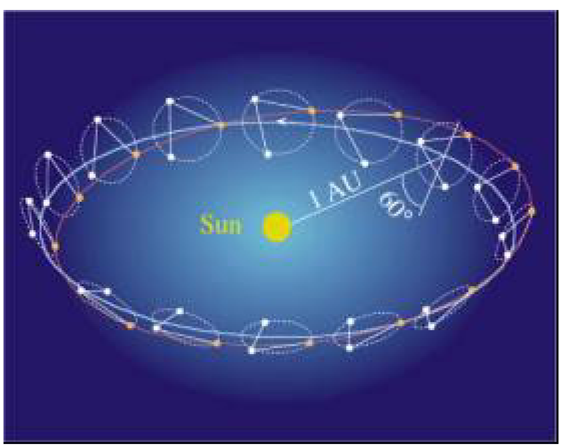

Figure D-13: Annual motion of LISA configuration

Small changes in the geometry of the formation still appreciably affect the phase measurement. The arm lengths slowly change throughout the year, with typical velocities of 1 m/s and maximal velocities of 15 m/s. This has the effect of putting a Doppler frequency on the beat signals that varies slowly with a period of one year. It also changes the angle between the arm lengths ±1°, requiring actively controlled articulation between the optic axes defining the arm lengths at a vertex. Pointing is discussed in Section E.4.5. Since the formation geometry is not actively maintained, evolution of the orbits set an ultimate limit on the mission lifetime of approximately 10 years.

LISA places no unusual demands on the launch vehicle. There is no unusual requirement on the launch window. An extended cruise phase and a propulsion module (to be jettisoned after final injection) are required to insert the spacecraft into the desired orbits.

D.3.3.2 Mission Requirements

Using the instrumentation concept summarized in Section D.3.2, we have developed requirements on subsystems and components from the performance requirements given in Section D.3.1. Like most precision measurements, the LISA design concept is built on a comprehensive and careful analysis of noise sources. Summary analyses are found in [Ref. D-2, D-3, D-4]; detailed analyses relating to the Disturbance Reduction System are found in [Ref. D-6, D-8]. In this section, the measurement requirements are allocated amongst contributing effects, where appropriate, and the associated subsystems are identified.

Table D-4 on Foldout D-1 traces the impact of the system level measurement requirements on subsystems. These allocations are compatible with direct calculation of the noise contributions expected from the conceptual design.

The performance requirement on acceleration noise associated with unwanted disturbances is allocated to potential sources, in the context of a detailed design concept. To allocate acceleration noise to various subsystems, it is necessary to look at contributing effects for each of the three categories, as shown in Table D-5 on Foldout D-1. Only the "sensitive" degree of freedom, i.e., the measurement axis, is discussed here. Other degrees-of-freedom have generally less restrictive requirements.

Noise in the measurement of the round trip optical path sets the limiting sensitivity of the LISA conceptual design in the middle and upper frequencies. Table D-6 on Foldout D-1 gives the allocation of "displacement" noise associated with the measurement system and identifies subsystem impacts.

D.3.3.3 Operations

LISA science operations are particularly simple; there is a single operating mode wherein data is collected. There is no pointing of the instrument or special observing campaigns. The science data analysis does require high data-collection duty cycles, as discussed in the next section. Brief outages on a weekly to monthly basis are anticipated for high gain antenna re-pointing or optimizing control systems.

LISA data collection is modest in volume with on-board reduction further reducing communications requirements (see Section D.3.4.1).

D.3.4 Data Reduction and Analysis

The objective of LISA is to detect and extract astrophysical information from gravitational waves generated by galactic and extragalactic sources. The data are analyzed in two steps. The first step, performed nominally on-board, uses TDI to form data combinations which are sensitive to gravitational waves, but in which the leading noise sources – laser phase noise, non-inertial motions of the optical benches, and ultra-stable-oscillator (USO) noise – are either canceled exactly or suppressed to negligible levels. These TDI combinations form the basic LISA science data set. The second step, performed on the ground, takes the TDI combinations and uses search and information extraction algorithms to obtain astrophysical information on the sources and wave properties from the TDI combinations.

The critical data-taking phase begins after the LISA formation is established, approximately one year after launch. Continuous data taking for the nominal life of the mission is planned, but our data gathering and analysis strategy is robust against data gaps.

The primary data gathered are time series of phase (or frequency) from the laser links connecting pairs of proof masses. After laser and clock frequency noise are removed, the data are down-sampled on-board for transmission to the ground. For on-orbit verification of LISA noise performance, determination of instrumental noise, and internal consistency checks among the TDI combinations, other TDI combinations are formed and down-sampled for transmission to the ground. Four TDI combinations are a complete dataset.

There are two modes of operation to form these TDI combinations, Verification Mode and Standard Mode.

Verification Mode is for testing and verification, as well as transmitting the following raw data to the ground: Doppler shifts on the optical links between proof masses on separated spacecraft; internal metrology between proof masses on a single spacecraft; and spacecraft-to-spacecraft metrology. TDI requires sampling of 18 combinations and, in this mode, transmission of about 6,000 science bits/second. This mode requires limited on-board storage (about 100 MB/day).

Standard Mode is the science operational mode. In the Standard Mode, the TDI combinations are formed on the spacecraft and only the four noise-cancelled data combinations are transmitted to the ground. At a 2 Hz sample rate, and conservatively allowing 32 bits/sample, this corresponds to only 256 science bits/second. This is about 2.8 MB/day, easily stored for downlink to the Earth as tracking passes become available.

D.3.4.1 Data Rate and Volume

The data rates and volumes produced by LISA are modest.

Data acquisition, storage, and transmission in the Standard Mode:

- Science data: 4 TDI combinations x 32 bit x 2 Hz = 256 bps
- Auxiliary data: 3 spacecraft x 100 bps = 300 bps
- Spacecraft Housekeeping: 3 spacecraft x 100 bps = 300 bps
- Total data: = 856 bps
- Packet data formatting: 5% overhead ≥ 900 bps
- Framing/encoding: 15% overhead ≥ 1 kbps

The total transmitted data volume for a five year mission is ~163 GB (raw data). The science data returned from the spacecraft are reduced to the four calibrated data channels at 2 Hz and 32 bits, yielding a total of about 40 GB (Level 2). The small data volumes imply that there are no stressing requirements for data archive and distribution. The raw science data can be served from a modest hardware platform, and the entire processed science data set can be distributed on the 2011 equivalent of a few 2002-era DVDs, and is easily archived and distributed.

D.3.4.2 Data Reduction, Analysis, and Archiving

There are many gravitational wave signals present in the science data. These are separated through template-fitting of their anticipated waveforms in the data reduction.

Some of the data reduction is performed on-board, and the remainder is performed in a science data facility. A specific plan for data analysis is a formulation product.

Tasks for reducing raw science data include:

- Data quality checks/drop out corrections
- Calibration of inertial sensor and interferometer data into standard Doppler/phase units
- Reduction of the GRS and interferometer data to four calibrated science data channels (four TDI modes)

The following data analysis tasks are required to detect and analyze source waveform:

- Identification of strong candidate periodic and non-periodic sources by template-fitting and removal by subsequent subtraction
- Searches for weak sources by further template-fitting and their removal by subtraction
- Diffuse background analysis

While the data volume is moderate, the ground-based computation per data byte is high. Estimates of the maximum computational analysis are based on waveform searches with M independent templates on a data set of N samples. Each search requires a maximum of several $\log_2 N$ computations per data sample. The number of computations per sample is of order several $M \log_2 N$.

Most individual gravitational wave sources are not expected to have significant harmonic content above about 0.03 Hz. For a one-year data set this implies about 2 $\times 10^6$ samples or about 50 M computations per sample. A teraflop cluster computer (expected to be widely available in 2011), is capable of about 10^4 searches per second, or about 10^9 searches per day. More typically, shorter intervals are used to search for sources. A one-month data set sampled at 0.06 Hz implies 1.5 $\times 10^5$ samples or about 10^{10} searches per day. A recent estimate of the number of template searches needed for a one-month detection of a gravitational capture event (the most challenging LISA analysis task identified) was between 10^9 to 10^{10}. Thus, a teraflop computer would be more than adequate to analyze LISA data 10 times faster than real time.